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## **Arc Spray Termination of Extended Foil Capacitors**

Aaron C. Hall, James F. McCloskey, David E. Beatty, Henry A. Padilla II, Luke H. Wyatt, and Stephen W. Othling

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Aaron C. Hall<sup>1</sup>, James F. McCloskey<sup>1</sup>, David E. Beatty<sup>1</sup>, Henry A. Padilla II<sup>1</sup>, Luke H. Wyatt<sup>2</sup>  
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## **Abstract**

Twin wire arc spray is evaluated as a termination method for the fabrication of extended foil wound capacitors. A full design of experiments is performed, analyzing various spray processing conditions and their effects on relevant electrical performance. Cross sectional metallography and electrical testing are used to evaluate potential damage caused by the deposition process as well as the overall quality of the finished capacitor sprayed under different conditions. Major findings are consistent with previously published work indicating that arc spray is a viable candidate for terminating foil capacitors.



## **ACKNOWLEDGMENTS**

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# 1. INTRODUCTION

## 1.1. Background on extended foil capacitors

Non-inductive or extended foil capacitors are often used in applications which require a wide range of operating temperatures, high pulse current rating and a wide range of operating frequencies. Their construction, similar to other wound capacitors, uses interleaved layers of a conductive metal foil between layers of a polymer film dielectric. The term extended foil refers to the arrangement of the foil and film layers shown in Figure 1, where alternating layers of metal foil extend beyond the ends of the polymer film. The outermost region consists of the loose foil ends, followed by a region of adjacent dielectric layers which may be sealed against the environment, and finally, the dielectric/foil region. After winding these layers around a mandrel, the anode and cathode must be terminated (not shown in Figure 1).

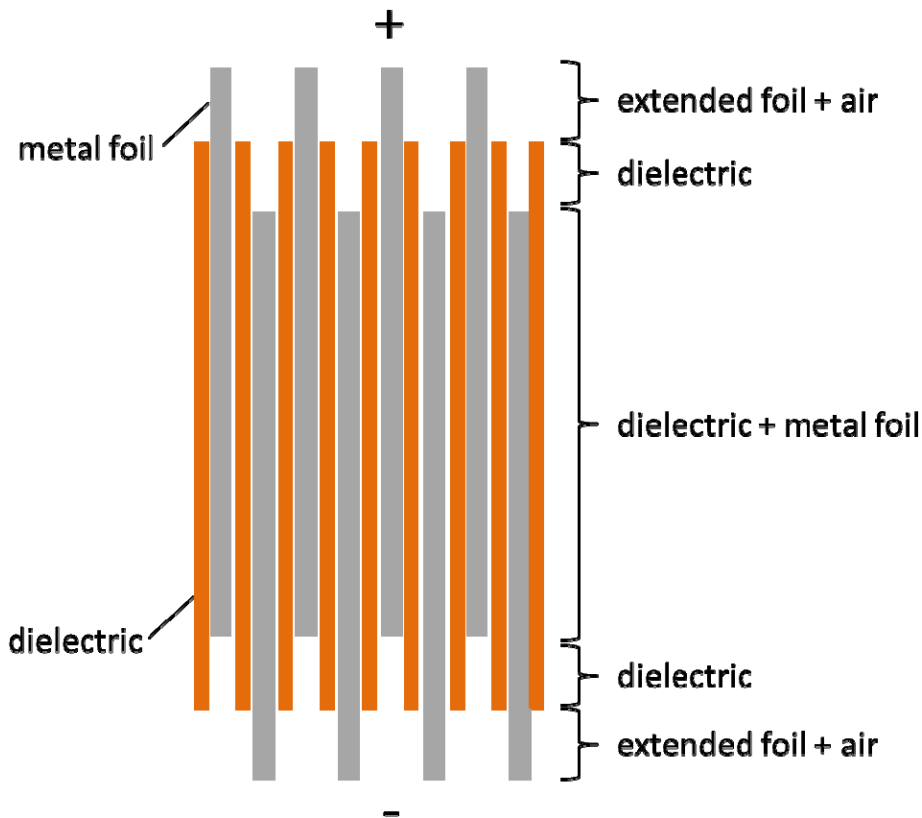


Figure 1. Cross-section schematic of extended foil capacitor.

## 1.2. Background on twin wire arc (TWA) spray

As a method of applying spray coatings, wire arc spray is a relatively straightforward and commonly used method. Any electrically conductive material that can be supplied in wire form has the potential to be sprayed via this method, shown schematically in Figure 2. Two wire sources are fed through electrically charged contact tips. When the wires exit the tips, they make contact, creating a high voltage electrical arc. The high temperatures reached in this process liquefy the materials, which are atomized by a propellant gas. The liquid droplets created by the atomization process are propelled downstream and deposit on the substrate. Example microstructures of arc sprayed Zinc using nitrogen as an atomizing gas are shown in Figure 3.

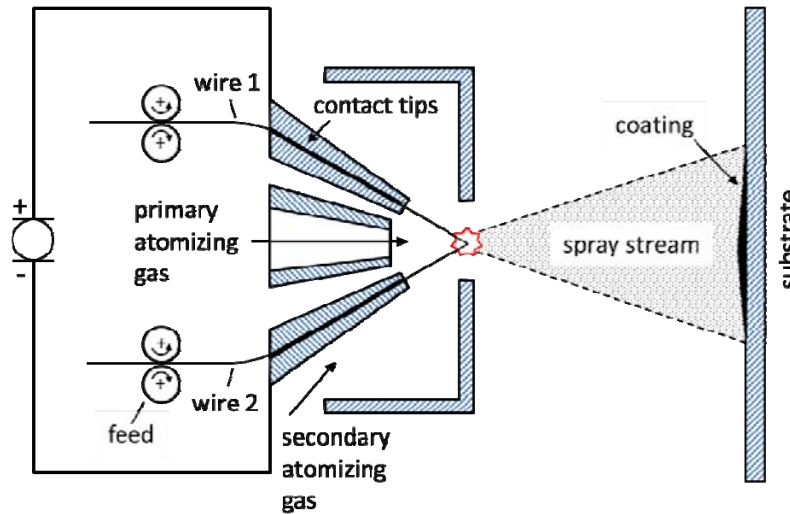


Figure 2. Schematic of twin wire arc spray system (adapted from [1]).

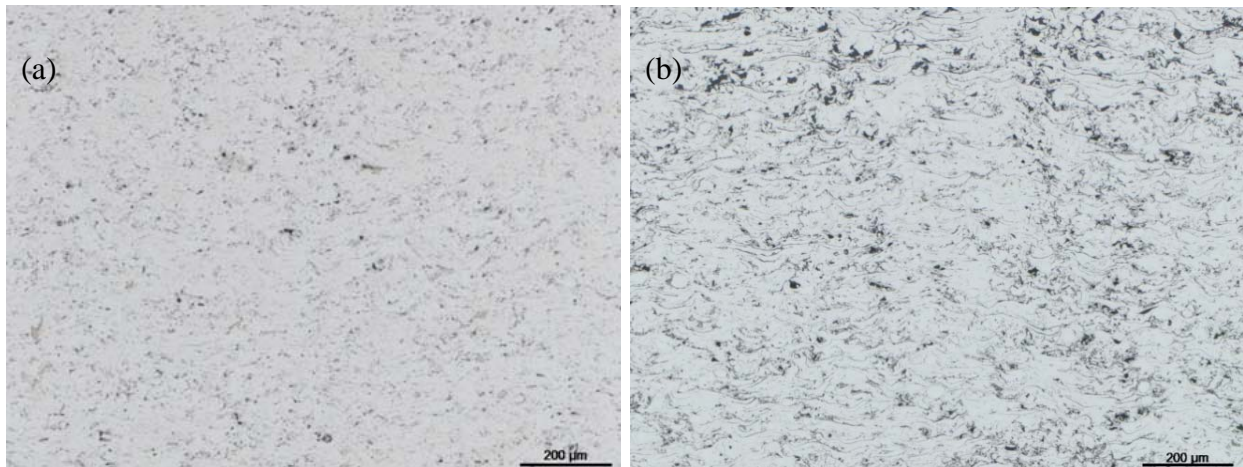


Figure 3. Optical micrograph showing typical Zinc microstructure sprayed with N2 atomizing gas in the (a) Hot and (b) cold condition. Images taken from [1].

Terminating extended foil capacitors using wire arc spray is well established in industry, but not well studied or documented in the open literature. Two common approaches are used:

- (i) Single layer of Babbitt (90%Sn – 7%Sb – 3%Cu)
- (ii) Initial sprayed layer of Zinc followed by a second coating of Babbitt

Babbitt is typically used as the top surface of the coating because it is easily soldered using a variety of solder alloys. Zinc, in comparison, is more difficult to solder and requires the use of a specific solder composition. Nevertheless, Zinc is used because in general it is known to have high adhesion strength and low heat capacity. In this work zinc was only investigated as a bond coating. While these two approaches are well known in the spray industry and both have been proven successful, relatively little literature documenting arc spray termination of capacitors has been found. The few papers that discuss arc sprayed termination of foil capacitors are a symposium paper from 1988 [2] and two SAND reports [3, 4]. In Mauldin's report a silver loaded epoxy was chosen over an arc sprayed coating because mechanical requirements were not met using the arc sprayed coating [3]. Specifically, Mauldin cites an inability to withstand the physical shock associated with the high current discharge of the system as the reason for choosing silver loaded epoxy as the capacitor termination material. In later work, Harris and colleagues report the direct comparison of arc sprayed Babbitt terminated capacitors and Ag loaded conductive epoxy terminated capacitors for high current applications (>20 kA with 50% reversal) [4]. In three types of destructive tests, (short term breakdown (STB) at -55°C, operational life (OPL) at 23°C and DC life (DCL) test at 74°C) the arc sprayed capacitors outperformed the Ag epoxy capacitors by margins of 4-500%. Additional information on the performance of Ag-epoxy capacitors for low current applications (1 kA with 10% reversal) may be found in reference [4]. The summary of those results is shown in

Table 1. These data are normalized and refer to different measurements depending on each test; see reference [2] for more detail.

**Table 1. Performance comparisons of Ag-epoxy and Arc Spray Babbitt electroding systems (adapted from [2]).**

	Ag-epoxy	Arc Spray
STB at -55°C	1.0	1.04
DCL at 74°C	1.0	1.44
OPL at 23°C	1.0	5.07

## 2. EXPERIMENTAL METHOD

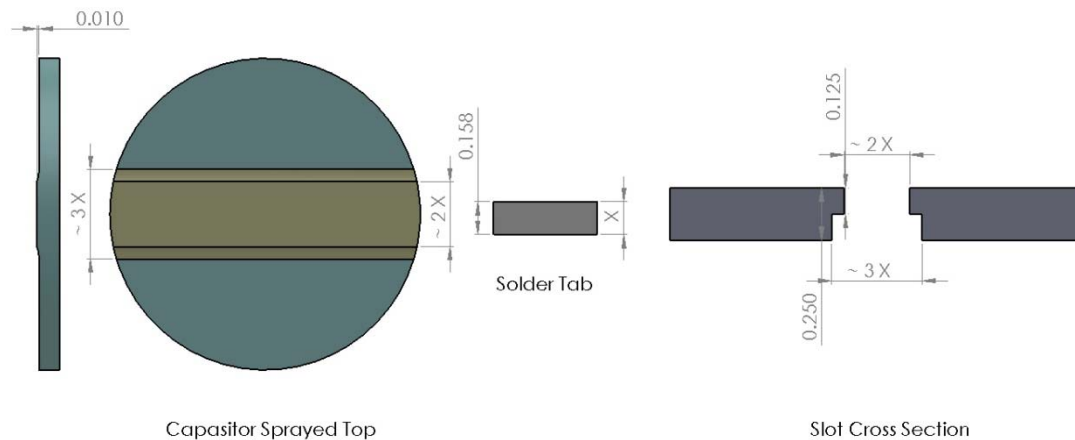
### 2.1. Equipment

The spray system used in these experiments is a Praxair™/TAFA™ model 8835 twin wire arc spray gun and controller, shown in Figure 4 (a). The 350-amp gun uses an electric drive which pulls the wires into the nozzle, creating an arc between the two contacting wires which liquefies the metal and accelerates droplets toward the substrate using whatever propellant gas is supplied. The gun is fixed to a rigid support frame, while the parts to be coated are mounted on the end of an ABB IRB 140 robot arm inside the spray booth (Figure 4 (b)). The parts are then rastered in front of the spray stream using a custom-built LabView robot control interface.

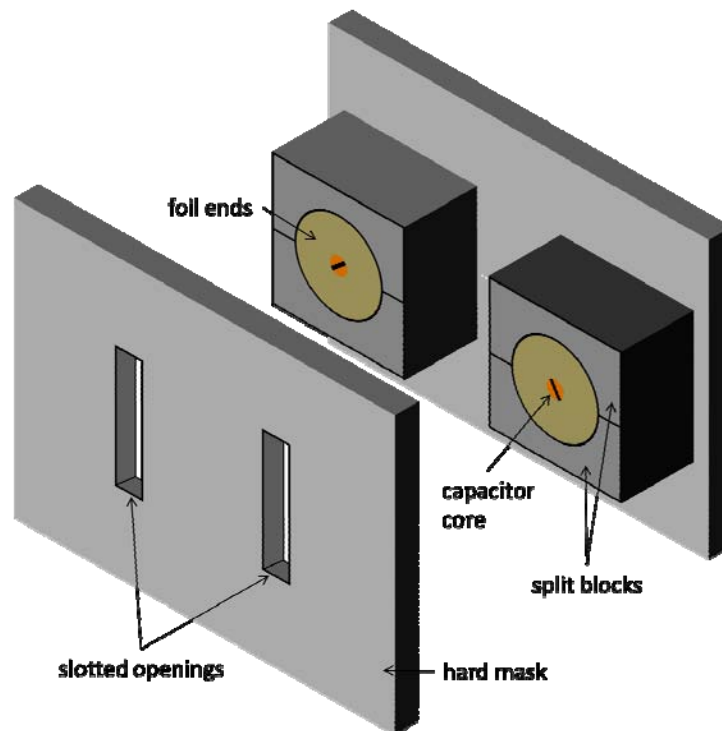


**Figure 4. (a) (top) Praxair/TAFA 8835 arc spray system. (b) (bottom) Arc spray gun is shown mounted near the robot arm inside the spray booth. In this photograph, the hard mask is attached to the ABB robot, with thermal spray tape covering one of the two slots.**

A hard mask was designed to control the sprayed coating on the capacitor ends based on the schematic shown in Figure 5. The mask is shown in Figure 6. Two capacitors are enclosed in split aluminum blocks, which are then held between two plates machined with slots matching the dimensions in Figure 5. The slots are undercut to allow a uniform thickness coating to deposit on the substrate and to facilitate removal of the mask without damaging the coating.



**Figure 5. Schematic defining the spray pattern mask.**



**Figure 6. Capacitors shown held in masking brackets.**

## 2.2. Design of Experiments

A series of experiments were designed based on earlier wire arc studies in order to screen atomizing gas (nitrogen or air), spray condition (Hot or cold), and coating material (Zinc, Babbitt or Zinc + Babbitt) to efficiently identify a baseline spray condition. The full factorial DOE is shown below in Table 2. Sixteen samples were required because each condition is run twice. The repeat is needed to be certain that these data are consistent. Varying Atomizing gas will change the oxide content and porosity of the coating, with Nitrogen giving both lower oxide and lower porosity. Varying the spray condition will vary the droplet size between fine and coarse as well as change the droplet temperature from Hot to cold. These spray conditions will be selected from earlier work. Varying the coating material will affect the coating properties including conductivity, adhesion strength, and substrate contact.

**Table 2. Full factorial design of experiments. One sample per spray run, each condition is repeated once.**

RunOrder	Atomizing Gas	Spray Condition	Coating Material
1	N <sub>2</sub>	Hot	Zinc + Babbitt
2	Air	Hot	Babbitt
3	N <sub>2</sub>	Cold	Zinc + Babbitt
4	N <sub>2</sub>	Hot	Zinc + Babbitt
5	N <sub>2</sub>	Cold	Zinc + Babbitt
6	Air	Cold	Zinc + Babbitt
7	Air	Hot	Zinc + Babbitt
8	Air	Hot	Zinc + Babbitt
9	Air	Cold	Babbitt
10	N <sub>2</sub>	Cold	Babbitt
11	Air	Cold	Zinc + Babbitt
12	N <sub>2</sub>	Hot	Babbitt
13	N <sub>2</sub>	Hot	Babbitt
14	N <sub>2</sub>	Cold	Babbitt
15	Air	Hot	Babbitt
16	Air	Cold	Babbitt

There are several parameters that need to be defined as part of the spray process, including wire feed rate, standoff distance, primary and secondary gas pressures and arc current. One concern in specifying 'Hot' and 'cold' spray conditions is whether either extreme would result in damage to the capacitor foils. Based on previous experience, three pairs of samples (6 total) were chosen to represent 'Hot' and 'cold' extremes for Zinc, Babbitt and Zinc/Babbitt coatings. These samples were chosen from Table 2 to determine whether to proceed with the full DOE. The parameter set points are shown in Table 3.



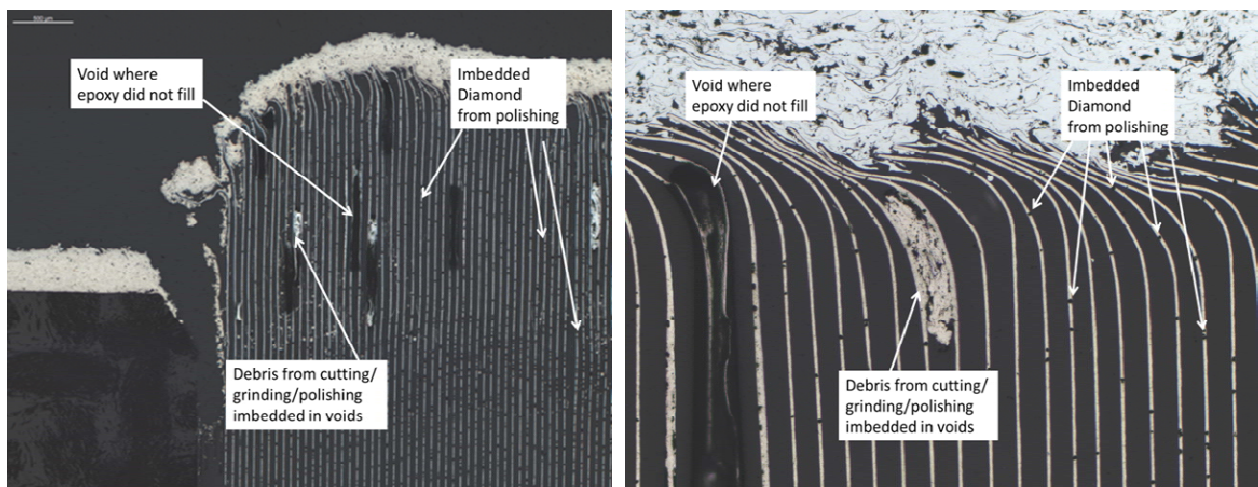
**Table 3. Arc Spray Conditions: Hot & Cold. \*See text for note regarding the AS-1 18” standoff condition.**

Sample Number	Sample/condition	Material	Planned Set-Point				
			Wire Feed Rate (in/s)	Standoff (in)	Primary Gas Pressure (psi)	Secondary Gas Pressure (psi)	Arc Current (amps)
1	AS-1 Hot	Zinc	15.84	6	50	29	200
2	AS-1 Hot*	Zinc	15.84	18	50	29	200
3	AS-2 Hot	Zn/Babbitt	15.84	6	50	29	200
4	AS-2 Cold	Zn/Babbitt	2.96	18	50	20	50
5	AS-3 Hot	Babbitt	15.84	6	50	29	200
6	AS-3 Cold	Babbitt	2.96	18	50	20	50

\*Sample AS-1 was not processed as intended for the “cold” condition. Wire feed rate, secondary gas pressure and arc current were set at the “Hot” condition (15.84 in/s, 29 psi, 200 amps) while the standoff distance was increased to the correct 18” distance for the “cold” condition. Due to a lack of additional capacitors to correct this, the planned “cold” condition for AS-1 was renamed ‘Hot 18”’ to indicate the mixture of set-points.

### 2.2.1. Microstructural Results

After spraying all capacitors were sectioned with a diamond saw, mounted in epoxy and polished using standard metallography practices. Some polishing artifacts are visible in these micrographs. Figure 7 identifies three artifacts: voids in the potting epoxy, debris generated by mechanical polishing embedded in those voids, and diamond particles embedded in the aluminum foils of the capacitor.



**Figure 7. Examples of polishing artifacts.**

### 2.2.1.1. Zinc Coatings

Figure 8 and Figure 9 show micrographs of Sample 1 and 2, Table 3. These samples are zinc coatings prepared at 6" and 18" standoff distances, respectively. Both coatings were sprayed at 200A. The coating in Figure 8 appears to be composed of two layers because the coating process was interrupted in order to measure the coating thickness. The mandrel of the capacitor in Figure 9 is recessed. This occurred on the drive end of each capacitor and is an artifact of the winding process that is not expected in the final product. It does not affect interpretation of these coatings.



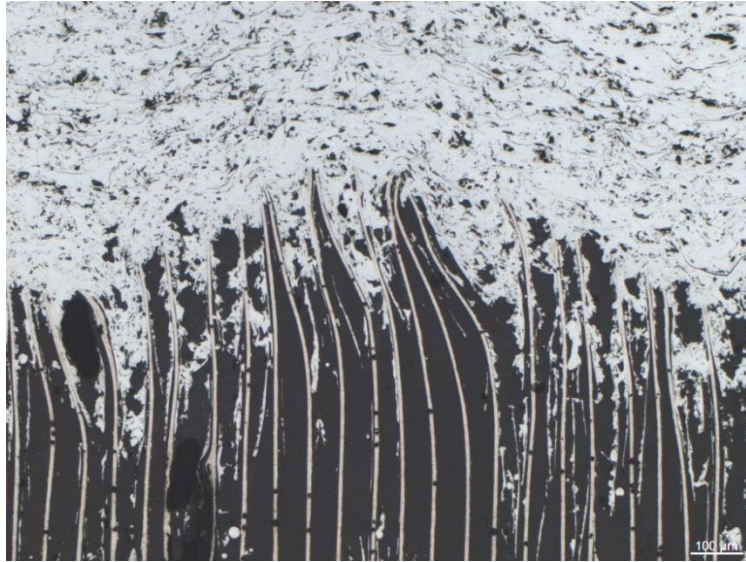
**Figure 8 Cross section of Sample 1, Table 3 showing a zinc coating sprayed at 6" standoff distance and 200A arc current. The apparent bi-layer in this coating is due to process interruption to check coating thickness.**



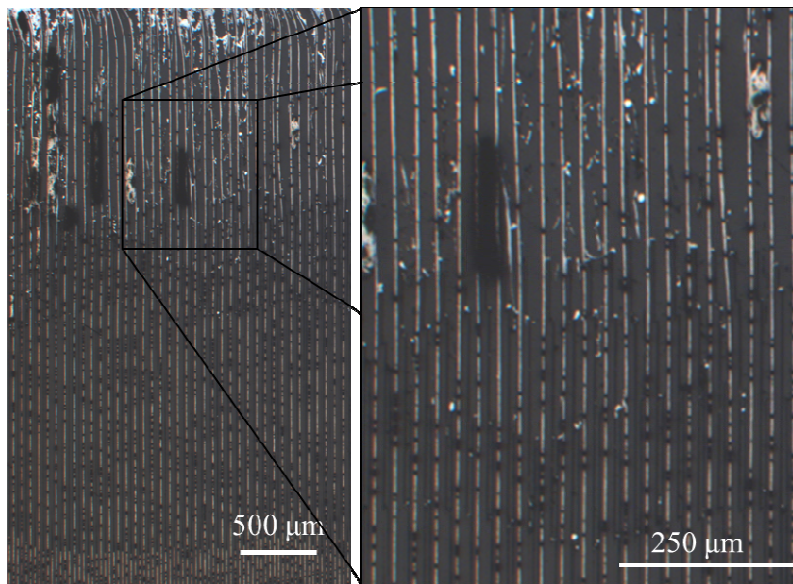
**Figure 9. Cross section of Sample 2, Table 3 showing a zinc coating sprayed at 18" standoff distance and 200A arc current. The recessed mandrel is an artifact of the winding process.**

Figure 10 and Figure 11 show a close-up of the coating-foil interface from Sample 1, Table 3. Zinc droplets that have penetrated between individual foils can be seen. Figure 11 shows penetration of dust particles up to 1 mm into the extended foil region. It is suspected that these particles are Zinc dust, but no chemical analysis was done to confirm this. These particle are not believed to be polishing debris because they are not associated with a void in the potting epoxy

used to prepare the sample for metallography. Instead they are completely surrounded by the potting epoxy suggesting that they were present in the capacitor at the time of potting. Zinc dust in this region of the capacitor is only a concern if it penetrates beyond the edge of the Mylar dielectric layer. No dust has been observed beyond the edge of the Mylar dielectric layer in the capacitors examined.



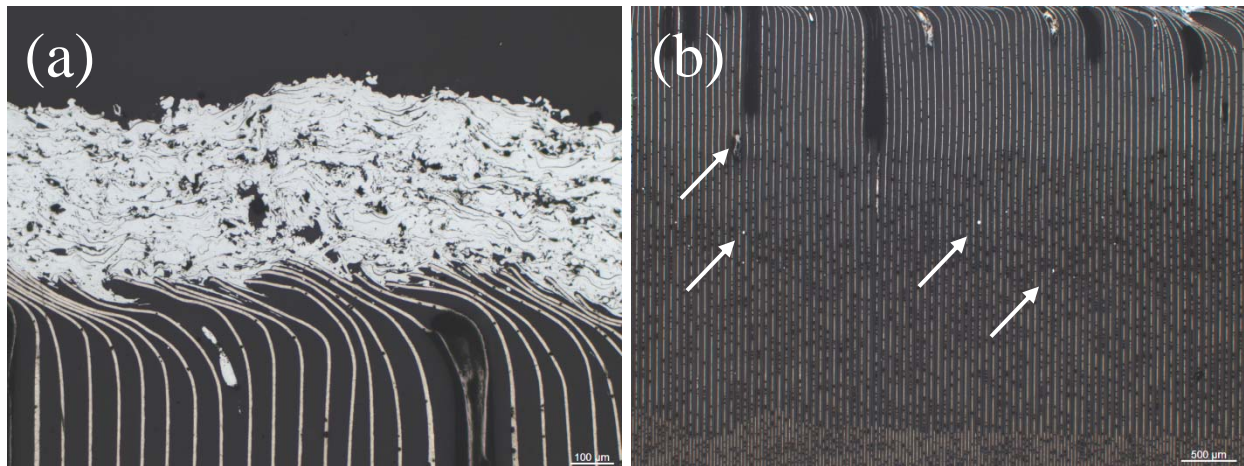
**Figure 10. High magnification image of the coating-foil interface for Sample 1, Table 3. Zinc splats can be seen penetrating between the foils.**



**Figure 11. Close-up cross sectional view of Sample 1, Table 3 showing Zn dust penetration between the foils. No zinc dust has penetrated beyond the edge of the Mylar dielectric layer.**



Figure 12 (a) and (b) show high magnification images of Sample 2, Table 3. This zinc coating was sprayed at 18” standoff and 200Amps arc current. The foil ends in Figure 12 (a) were bent prior to spraying. Dust were again observed to have penetrated between the extended foils.



**Figure 12. High magnification images of Sample 2, Table 3. Image (a) shows the coating – foil interface. Bending of the foil ends occurred prior to deposition. Image (b) shows Zn particles that have penetrated the extended foil region to depths of up to 2 mm.**

#### **2.2.1.2. Sample AS-2: Zinc/Babbitt Hot & Cold**

Figure 13 and Figure 14 show micrographs of Samples 3 and 4, Table 3, respectively. In both cases the coatings are multilayers with Zinc as the bottom layer and Babbitt as the top layer. Both layers of the coating shown in Figure 13 were deposited at 6” standoff distance and 200 Amps arc current. Both layers of the coating shown in Figure 14 were deposited at 18” standoff distance and 50 Amps arc current. Both coatings were prepared using the same spray path and traverse speed. The hotter deposition condition (Sample 3, Figure 13) produced a thicker coating. This is due to increased wire feed rate at the higher amperage arc current condition. Arc current and wire feed rate are, by necessity, coupled in a twin wire arc system because the wire feed rate must match the wire atomization rate in order to maintain a stable arc.

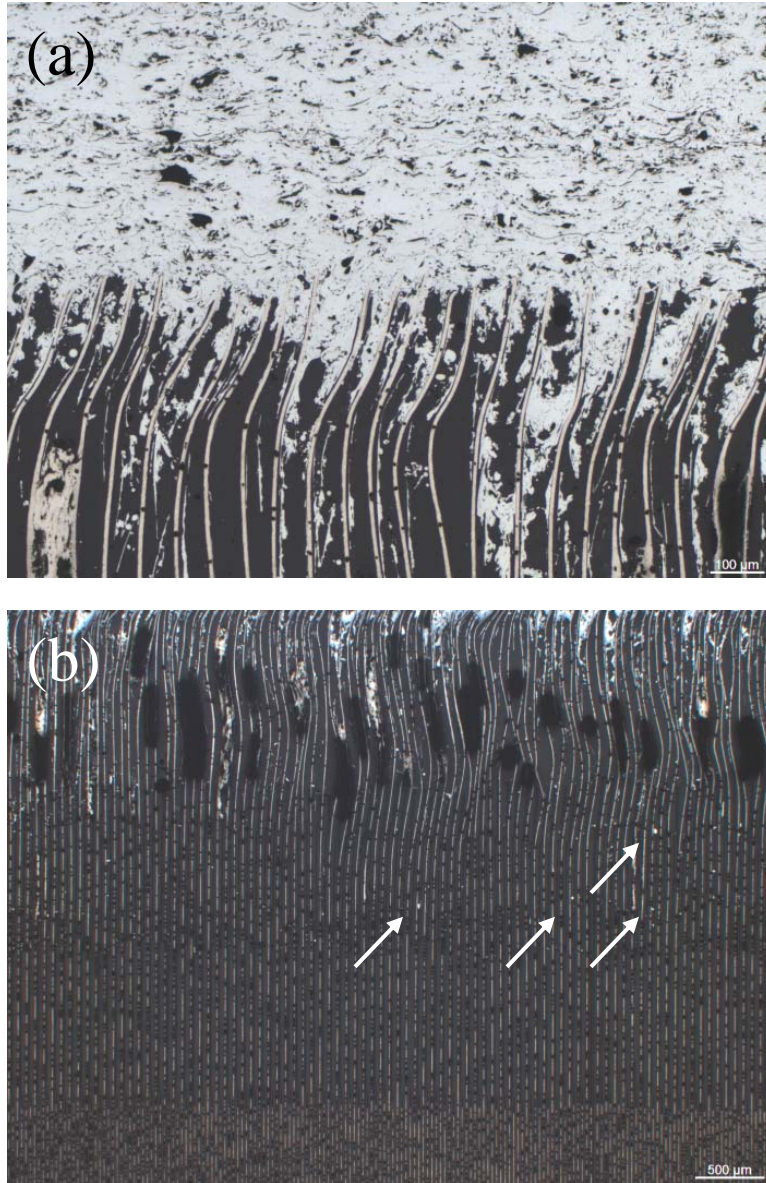


**Figure 13 Cross section of Sample 3, Table 3 showing a two layer coating sprayed at 6" standoff distance and 200A arc current. The apparent bi-layer in this coating is due to composition change. The top layer is Babbitt the lower layer is Zinc.**



**Figure 14. Cross section of Sample 4, Table 3 showing a two layer coating sprayed at 18" standoff distance and 50A arc current. The apparent bi-layer in this coating is due to composition change. The top layer is Babbitt the lower layer is Zinc**

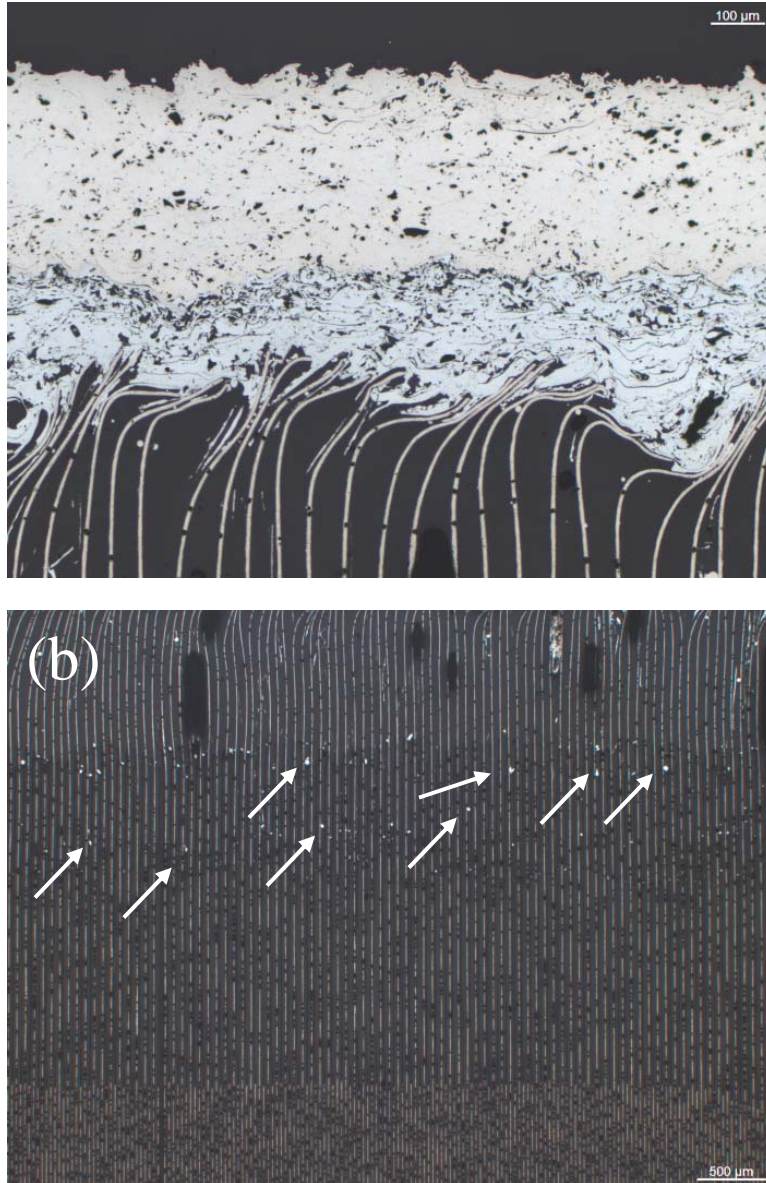
Figure 15 shows higher magnification micrographs of the Zinc/Babbitt coating deposited on Sample 3. The field of view in Figure 15 shows only the Zinc layer. Penetration of the Zinc splats between the extended foils as well as dust penetration deep within the extended foil region can be seen. The dust does not penetrate beyond the edge of the Mylar dielectric material.



**Figure 15. Micrographs of the coating-foil interface in Sample 3, Table 3 showing (a) zinc splats penetrating between the extended foils and (b) isolated Zinc particles penetrating deep within the extended foil region.**

Figure 16 shows high magnification micrographs of the dual layer coating from Sample 4, Table 3. The coating-foil interface and dust penetration are similar to Samples 1, 2, and 3; as expected.



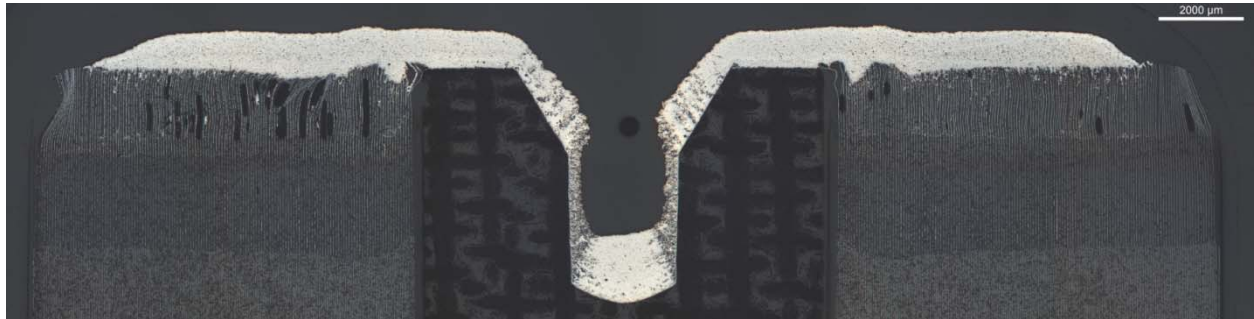


**Figure 16. Micrographs showing the coating-foil interface region of Sample 4, Table 3. Splashing and dust penetration are similar to Samples 1, 2, and 3; as expected.**

### **2.2.1.3. Sample AS-3: Babbitt Hot & Cold**

Figure 17 and Figure 18 show micrographs of Samples 5 and 6, Table 3, respectively. In both cases the coatings are Babbitt. The coating shown in Figure 17 was deposited at 6" standoff distance and 200 Amps arc current. The coating shown in Figure 18 was deposited at 18" standoff distance and 50 Amps arc current. Both coatings were prepared using the same spray

path and traverse speed. As before, the hotter deposition condition (Sample 5, Figure 17) produced a thicker coating.



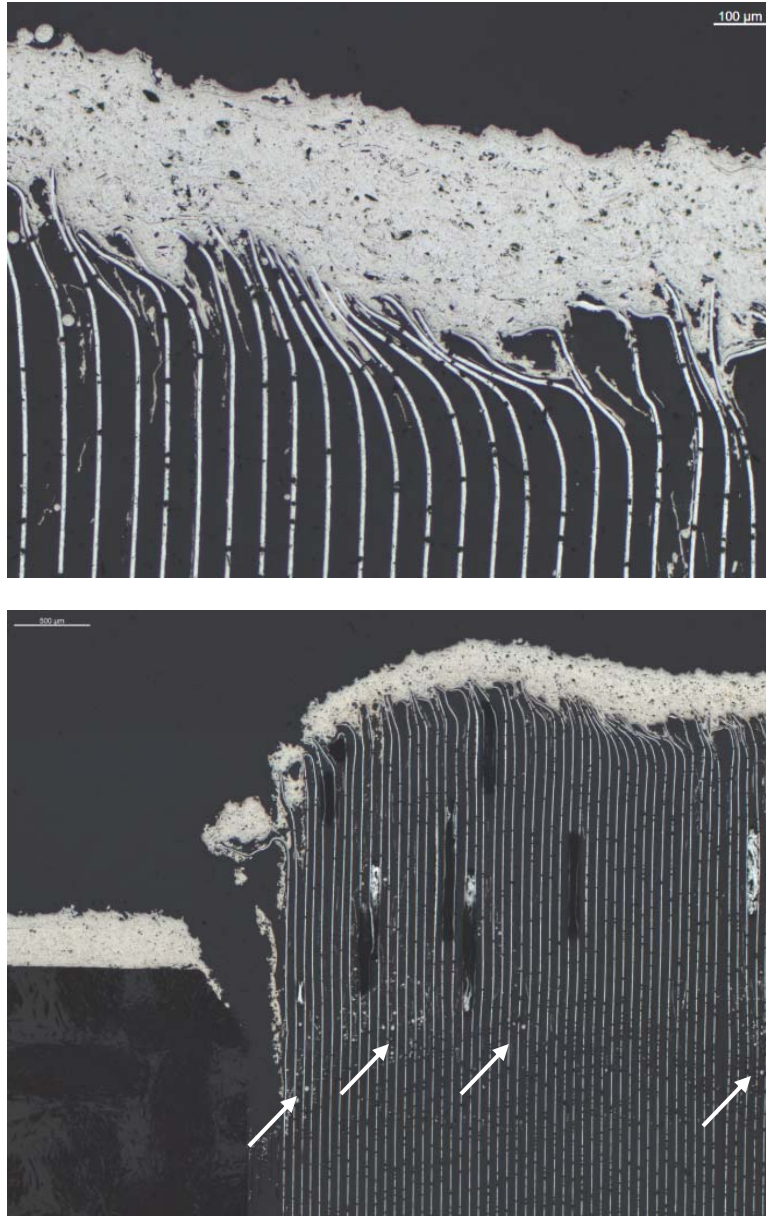
**Figure 17 Cross section of Sample 5, Table 3 showing Babbitt coating sprayed at 6" standoff distance and 200A arc current.**



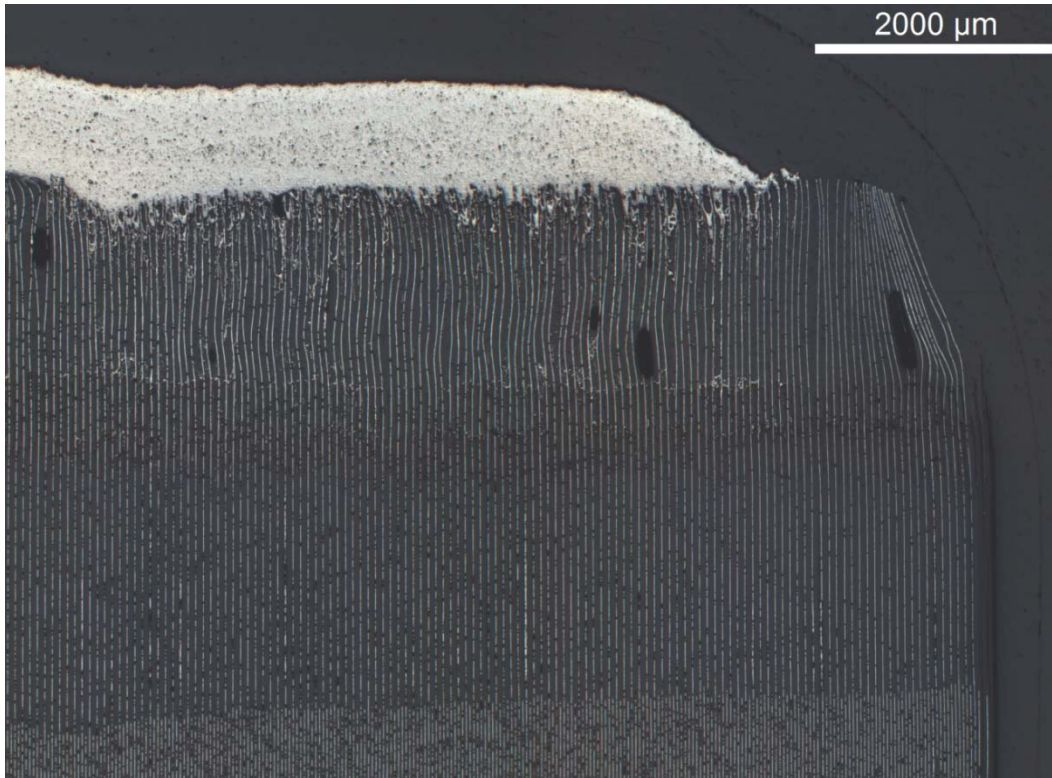
**Figure 18. Cross section of Sample 6, Table 3 showing Babbitt coating sprayed at 18" standoff distance and 50A arc current.**

Figure 19 and Figure 20 show micrographs of the coating-foil interface in Samples 5 and 6. Splat behavior and dust penetration are similar to Samples 1-4. As before, the Babbitt dust does not penetrate beyond the Mylar dielectric and is not thought to present a risk to the performance of the capacitor.





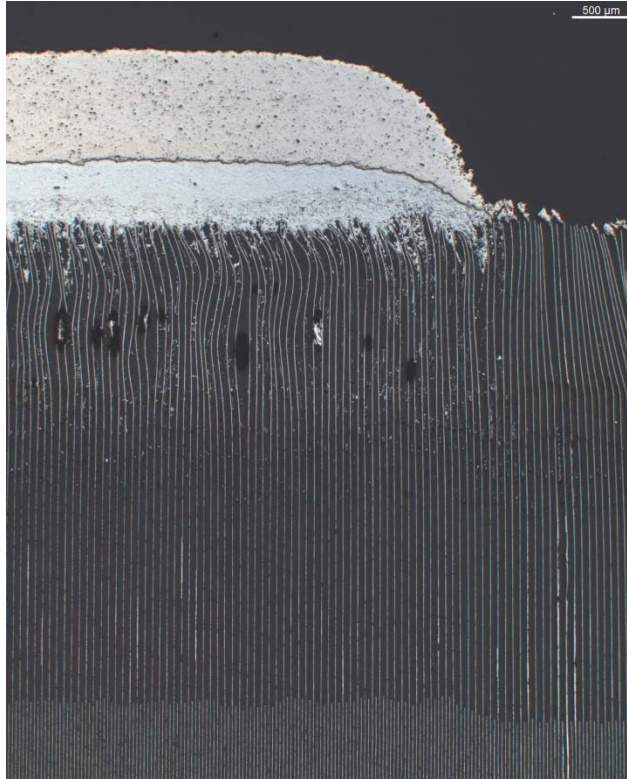
**Figure 19. Micrograph of Sample 6 showing penetration of Babbitt splats and dust between the extended foils.**



**Figure 20. Cross section of Sample 5, Table 3 showing penetration of dust.**

### *2.2.2. Dust Penetration Between Extended Foils*

A follow up experiment was conducted to determine if addition of an air knife across the spray plume could reduce dust penetration between the extended foils. This is a relatively well known approach used in the spray industry to reduce dust entrapment in thermal sprayed coatings. Extended foil capacitors were sprayed at the Babbitt and Zinc + Babbitt conditions shown in Table 3. Each of the four capacitors was cross sectioned and metallographically polished after spraying. Figure 21 shows a representative cross section of one of these capacitors. In all cases, addition of the air knife did not significantly affect dust entrapment. This does not mean that dust entrapment cannot be prevented, simply that the first attempt to do so was unsuccessful. It is important to recognize that the presence of the Mylar material between the aluminum foils does prevent entrapped dust from penetrating far enough to have an effect on the electrical performance of the capacitor or to create a risk of shorting.



**Figure 21 Cross Section a capacitor sprayed at the 6” standoff distance, 200 Amp condition using Zinc + Babbitt and an air knife to reduce dust entrapment between the foils. This approach was not successful, but the dust does not penetrate beyond the Mylar.**

## **2.3. Electrical Testing**

### *2.3.1. Parameters*

In order to quantify the performance of the capacitors and identify the connection to the processing conditions, several parameters of interest were measured and recorded, and are defined below:

Capacitance,  $C$  [ $\mu\text{F}$ ] – charge ( $Q$ ) held in a capacitor when a given potential ( $V$ ) is applied between leads

$$C = \frac{Q}{V}$$

Dissipation Factor, DF – measure of loss in the capacitor, defined as the equivalent series resistance divided by the reactance,  $X_C$ . Reactance is the effective AC resistance at a given frequency. It is the imaginary component, which together with resistance, make up the impedance. Reactance can be inductive ( $X_C > 0$ ), capacitive ( $X_C < 0$ ) or zero.

$$DF = \frac{ESR}{|X_C|}$$

Insulation resistance, IR [nA] – the electrical resistance across the terminals of a capacitor.

Equivalent Series Resistance, ESR [mΩ] – the sum of the in-phase AC resistance, including resistance of the dielectric, foil material and terminal leads at a particular frequency.

Resonant frequency,  $f_{res}$  [MHz] – frequency at which a capacitor, modeled as an RLC circuit, oscillates.  $L$  is the ESL of the capacitor.

$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

Calculated Equivalent Series Inductance, ESLcalc [nH] – inductance caused by the electrodes and leads. ESL sets the resonator point of a capacitor.

Measurement of ESR and ESL within a capacitor is somewhat difficult due to their small magnitude compared to the capacitance of the capacitor. A resonant frequency technique was used to extract these two parameters. A capacitor is made up of some capacitance, resistance, and inductance in series together; these three components form a simple series RLC oscillator whose resonant frequency is given by  $f_{res} = \frac{1}{2\pi\sqrt{LC}}$ , where  $L$  is the ESL of the capacitor and  $C$  is its capacitance.

By using an impedance analyzer to measure the impedance of each capacitor over a spectrum of frequencies near the capacitor's resonance, we can determine both the ESR and the ESL of the capacitor. Resonance in a series RLC oscillator is the point at which the reactance associated with the inductor cancels out the inductance associated with the capacitor. At this point all of the impedance in the circuit is at a minimum and also equal to the resistance of the circuit. Thus when looking at the impedance analyzer spectrum for each capacitor, the ESR is determined by finding the minimum impedance value along. The frequency at which this occurs is the capacitor's resonant frequency from which ESL can be calculated.

Measurement of IR is essentially a measurement of how “leaky” the capacitor is. This can be accomplished with a high-voltage power supply and a precision ammeter. A high voltage is applied to the capacitor and the current through the capacitor measured. If we allow the capacitor long enough to charge (say, two minutes), then the residual current flowing through the capacitor is considered to be its leakage current. By application of Ohm's Law ( $V = IR$ ) and knowledge of the applied voltage at which the leakage current was measured, the value of leakage current can be turned into an IR value.





### 3. RESULTS

#### 3.1. DOE Analysis

Table 4 lists the DOE test matrix along with the resulting values that were established using the methods described in the previous section. Sample 5 was found to have a fatal short after the leads were attached to the coating, and as a result did not result in meaningful measurements for capacitance, dissipation factor, insulation resistance and equivalent series resistance.

**Table 4. Electrical testing results of DOE. Sample 5 resulted in an electrical short after potting epoxy was applied the capacitor ends; consequently only  $f_{res}$  and ESL values could be reported.**

Run	Atomizing Gas	Spray Condition	Coating Material	C [ $\mu$ F]	DF	IR [nA]	ESR [m $\Omega$ ]	$f_{res}$ [MHz]	ESL <sub>calc</sub> [nH]
1	N <sub>2</sub>	Hot	Zn/Babbitt	0.4453	0.00244	7.2	8.923	1.775	18.05
2	Air	Hot	Babbitt	0.4503	0.00235	8.17	2.952	1.725	18.9
3	N <sub>2</sub>	Cold	Zn/Babbitt	0.4517	0.00258	6.34	33.104	1.55	23.34
4	N <sub>2</sub>	Hot	Zn/Babbitt	0.4421	0.0024	6.8	11.921	1.525	24.64
5	N <sub>2</sub>	Cold	Zn/Babbitt	*	*	*	*	1.75	18.38
6	Air	Cold	Zn/Babbitt	0.4474	0.00253	7.49	19.316	1.55	23.57
7	Air	Hot	Zn/Babbitt	0.4461	0.00257	10.11	37.08	1.475	26.1
8	Air	Hot	Zn/Babbitt	0.4546	0.00241	9.18	18.709	1.475	25.61
9	Air	Cold	Babbitt	0.4481	0.0025	9.34	24.246	1.575	22.79
10	N <sub>2</sub>	Cold	Babbitt	0.4493	0.00247	8.03	24.49	1.525	24.24
11	Air	Cold	Zn/Babbitt	0.4483	0.00241	5.92	17.193	1.5	25.11
12	N <sub>2</sub>	Hot	Babbitt	0.4501	0.0024	2.28	20.833	1.675	20.06
13	N <sub>2</sub>	Hot	Babbitt	0.4574	0.00241	7.83	13.38	1.475	25.45
14	N <sub>2</sub>	Cold	Babbitt	0.4541	0.00247	9.4	23.484	1.55	23.22
15	Air	Hot	Babbitt	0.4465	0.00244	7.46	12.913	1.55	23.61
16	Air	Cold	Babbitt	0.4425	0.00247	5.64	12.03	1.5	25.44

##### 3.1.1. Residual Analysis

The data shown in Table 4 were entered and analyzed in Minitab®. The residual analysis plots for each measured parameter are shown in Figure 22-Figure 27. The residuals are approximately normally distributed, randomly distributed around the respective fits and show no trends associated with the order of observation. The DOE only provides 16 data points for each measured value, which explains why the distributions are only approximately normal. The meaning of these results are that the DOE was unbiased by observation order.

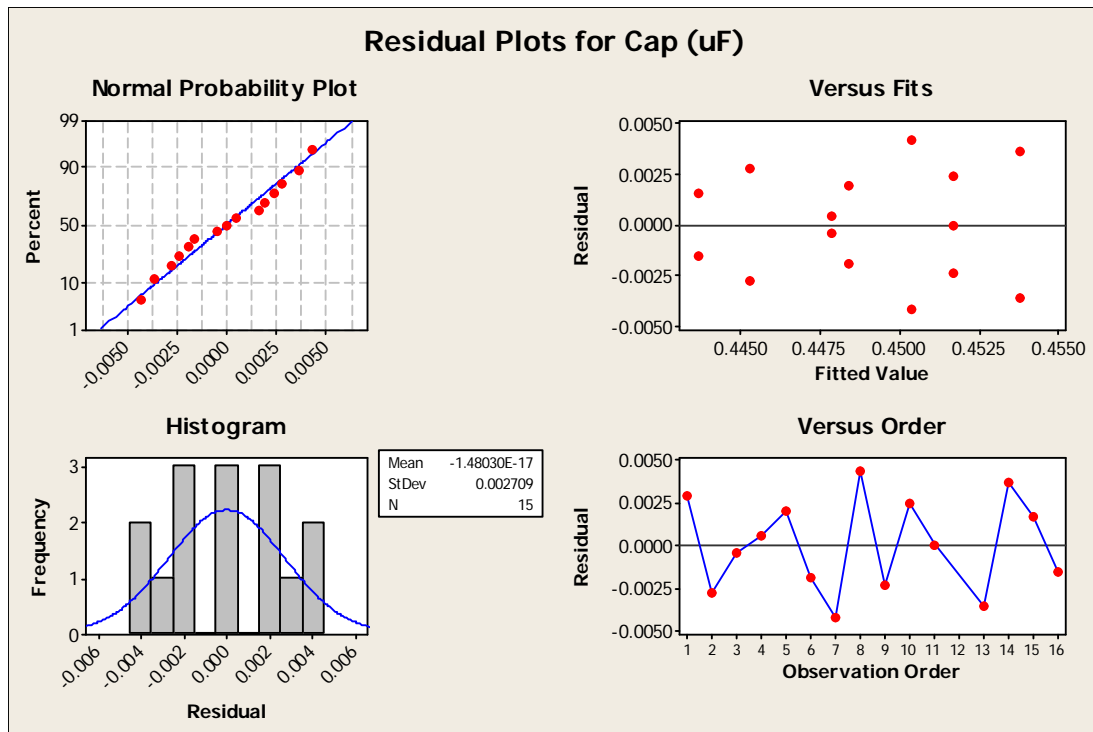


Figure 22. Residual plots for capacitance.

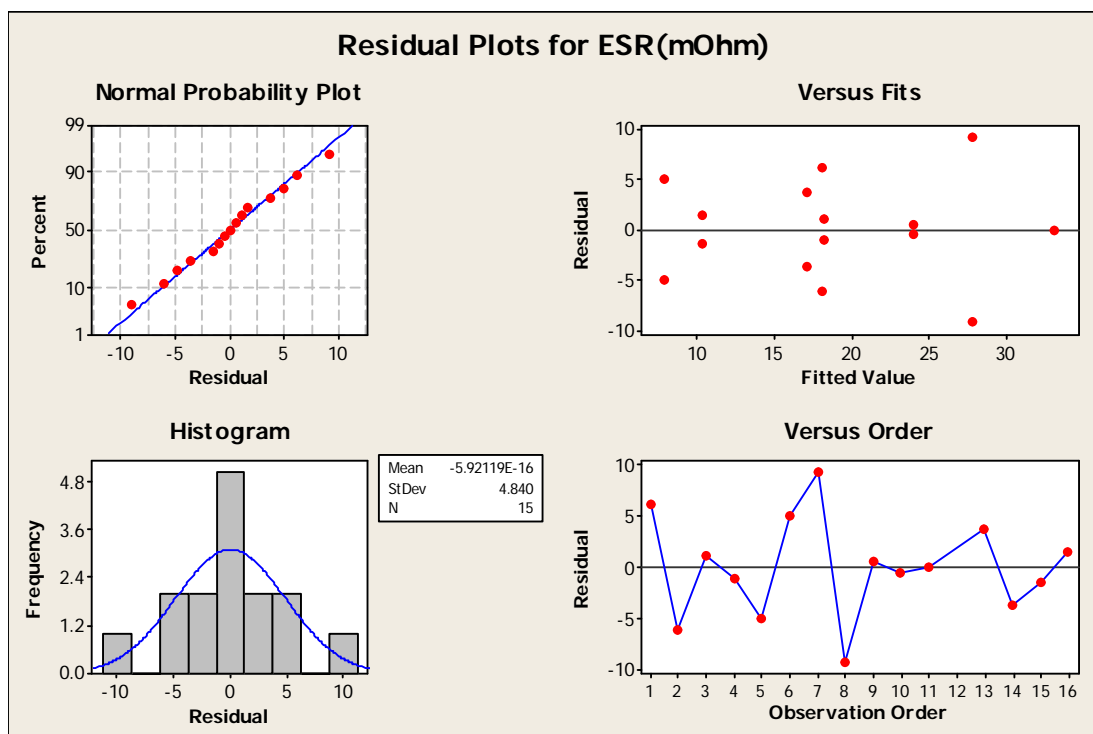
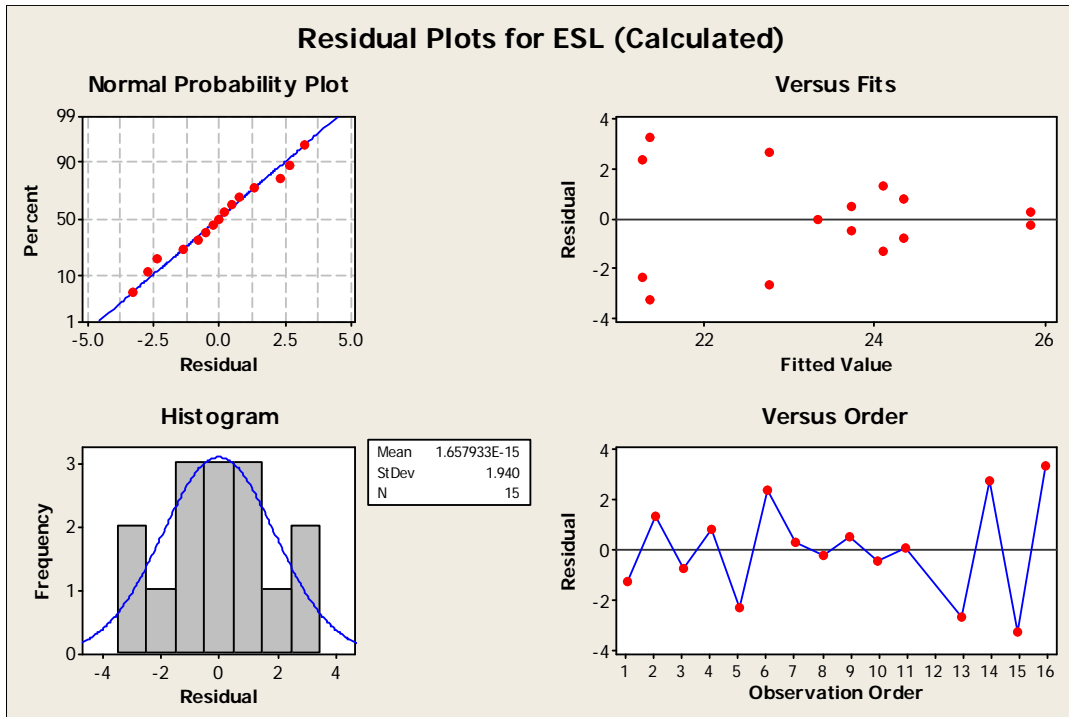
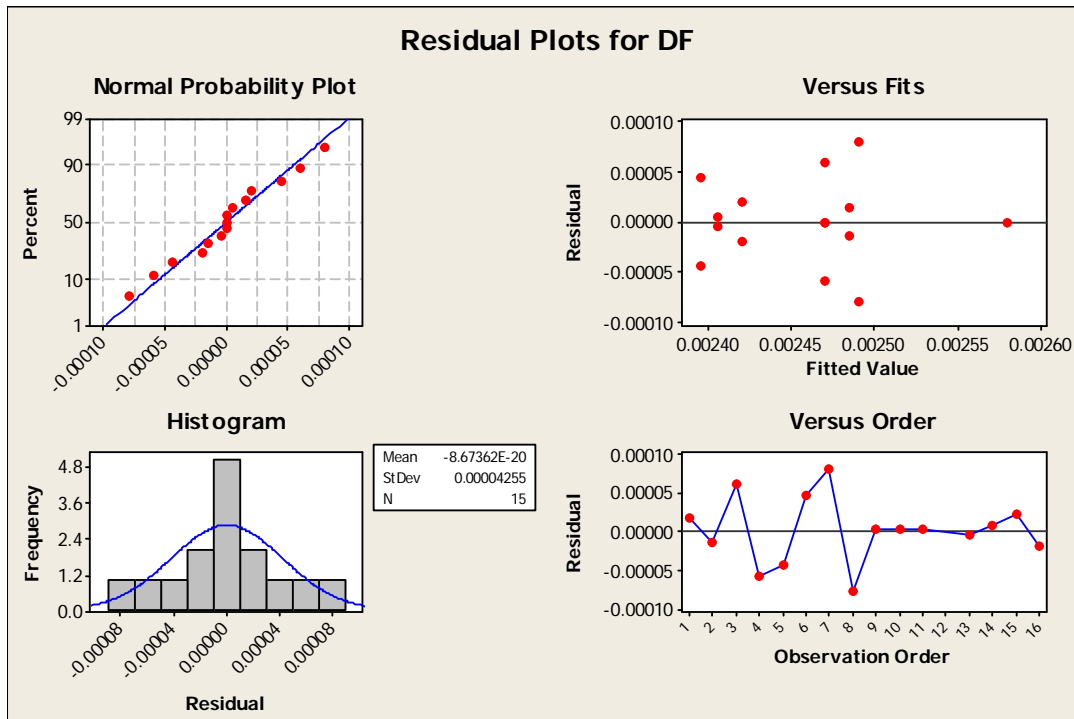


Figure 23. Residual plots for equivalent series resistance (ESR).

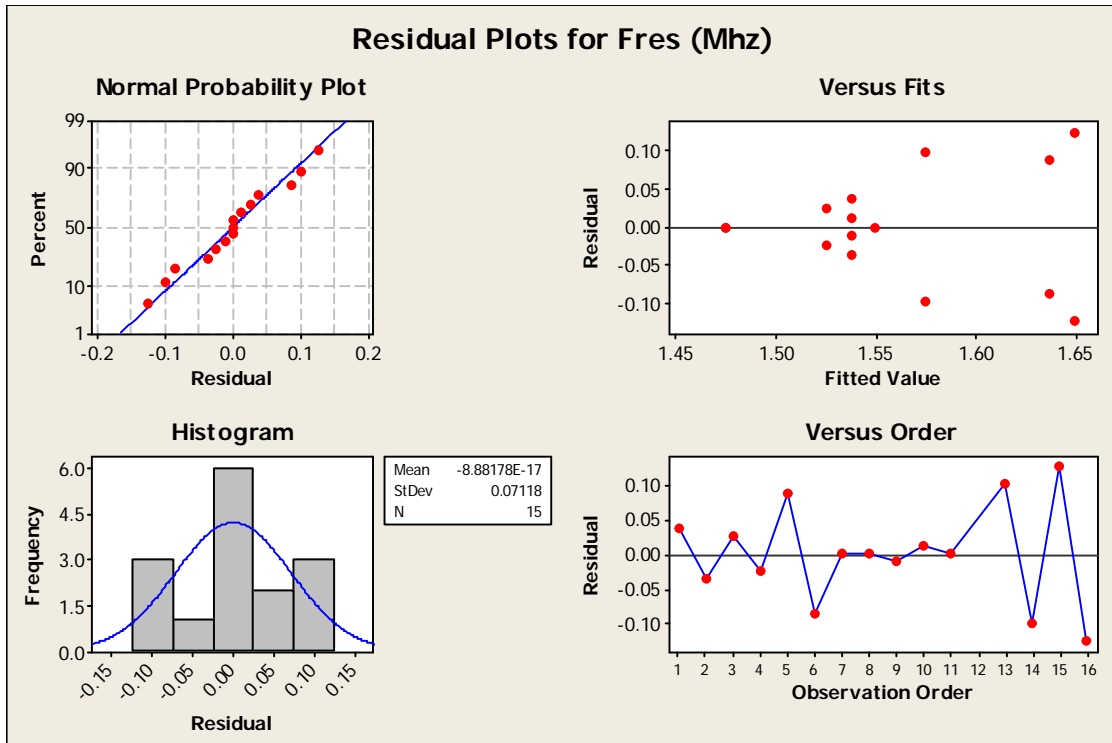




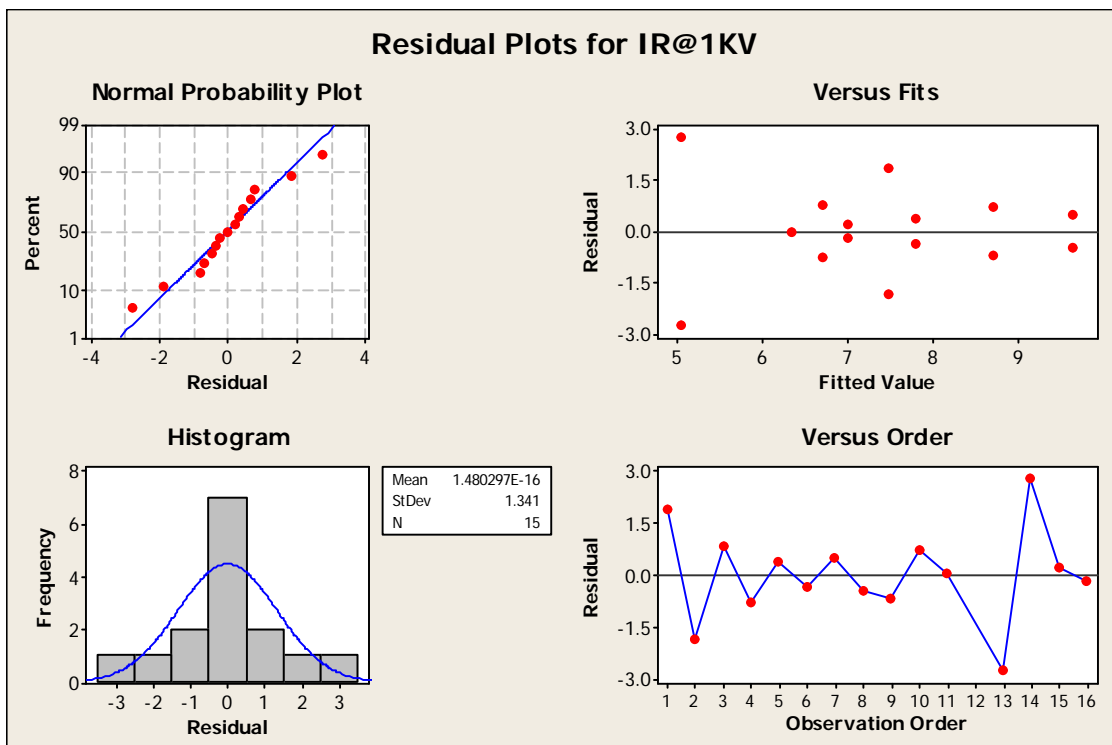
**Figure 24. Residual plots for equivalent series inductance (ESL).**



**Figure 25. Residual plots for dissipation factor (DF).**



**Figure 26. Residual plots for resonant frequency (fres).**



**Figure 27. Residual plots for insulation resistance (IR) at 1kV.**

### 3.1.2. Main Effects Analysis

Figure 28 and Figure 29 show main effects plots for ESR and ESL, respectively. The ANOVA analysis conducted on these data showed that at a 95% confidence level choice of spray condition and choice of coating material significantly affected capacitor ESR. The main effects plots illustrate how strongly atomizing gas, Hot/cold spray condition and coating material affect ESR or ESL while holding the other spray parameters constant. In Figure 28, it is clear that atomizing gas has little effect on ESR (the graph has a small slope), while spray condition and coating material have large effects on ESR (the graphs have a large slope). The conditions which *minimize* ESR are Hot spray conditions using a Babbitt-only coating.

From Figure 29, it is clear that atomizing gas has the strongest effect on ESL, while spray condition and coating material have negligible effects on ESL. The ANOVA analysis conducted on these data showed that at a 95% confidence level choice of atomizing gas significantly affected capacitor ESL. The conditions which *minimize* ESL appear to be using nitrogen as an atomizing gas. The use of a Hot spray condition with a Babbitt-only coating only provides a marginal improvement in ESL. This resulted in an average ESR of 16.5 m $\Omega$ .

Overall, these data suggest that atomizing with nitrogen in a Hot spray condition using a Babbitt-only coating is the ideal setup to minimize *both* ESR and ESL. The ESR and ESL values for these conditions (taken from Table 4, samples 12 and 13) are 17.11 m $\Omega$  and 22.76 nH, respectively.

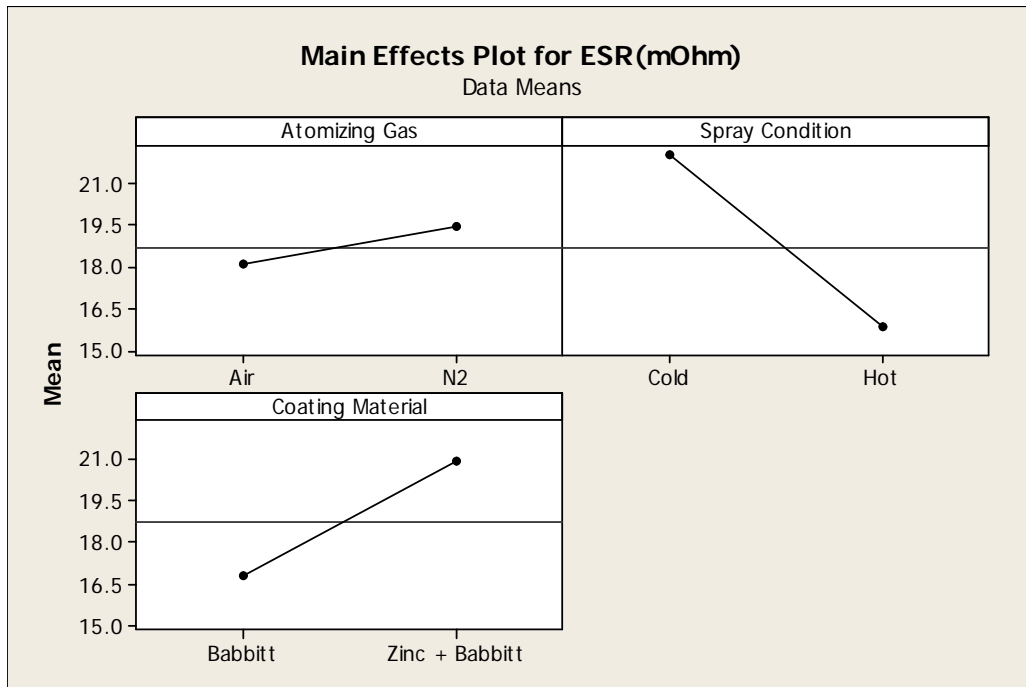
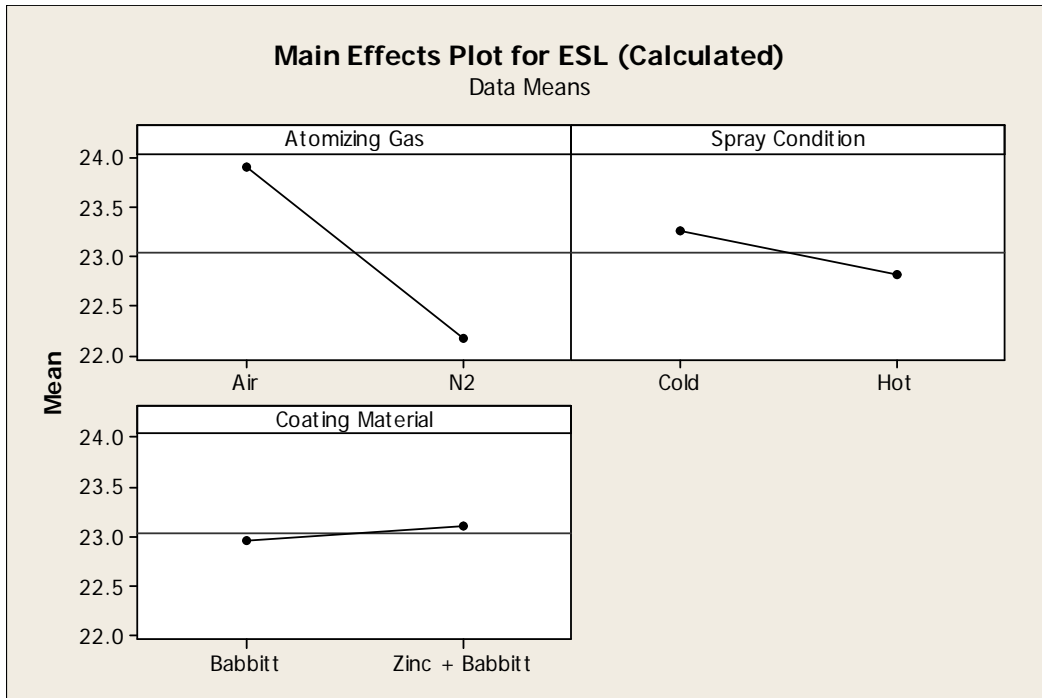


Figure 28. Main effects plot for ESR (m $\Omega$ ).



**Figure 29. Main effects plot for ESL (nH).**

### 3.1.3. Interaction Effects Analysis

Interaction plots help to identify situations when the effect of one factor is dependent upon the level of the other factors. Figure 30 shows that the effect of Spray condition and coating material on ESR is reversed by the choice of atomizing gas. Figure 31 shows that the effect of coating material choice on ESL is reversed by choice of atomizing gas and spray condition. This information is extremely important as process choices are being made. It also shows why air is not a substitute for Nitrogen as an atomizing gas.

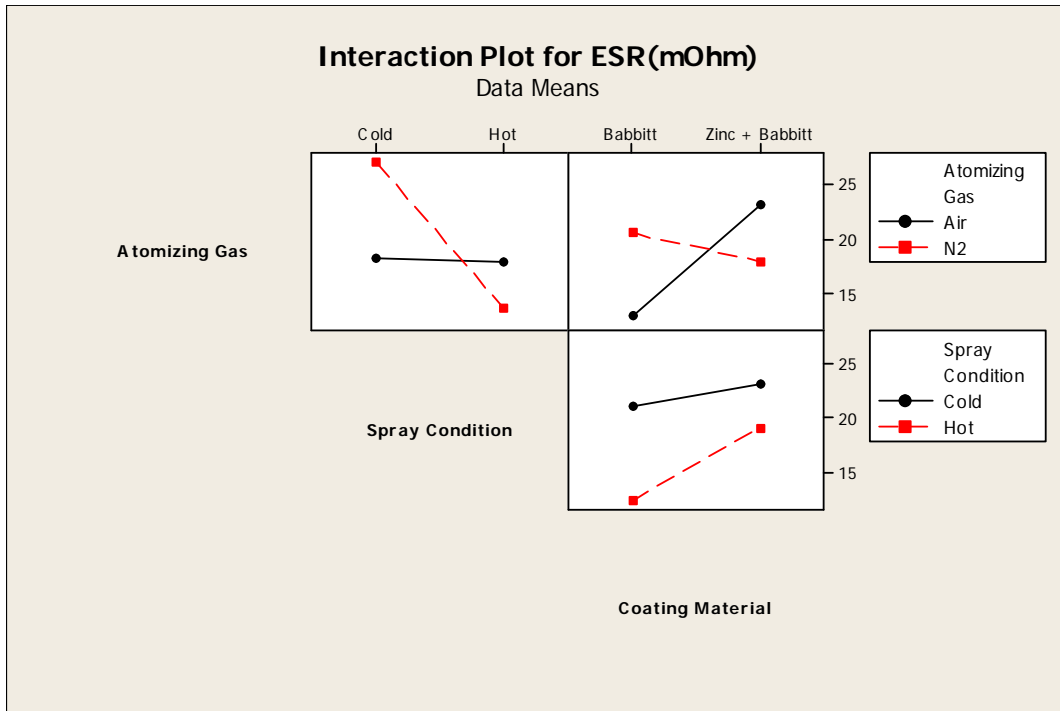


Figure 30. Interaction plots for ESR (mΩ).

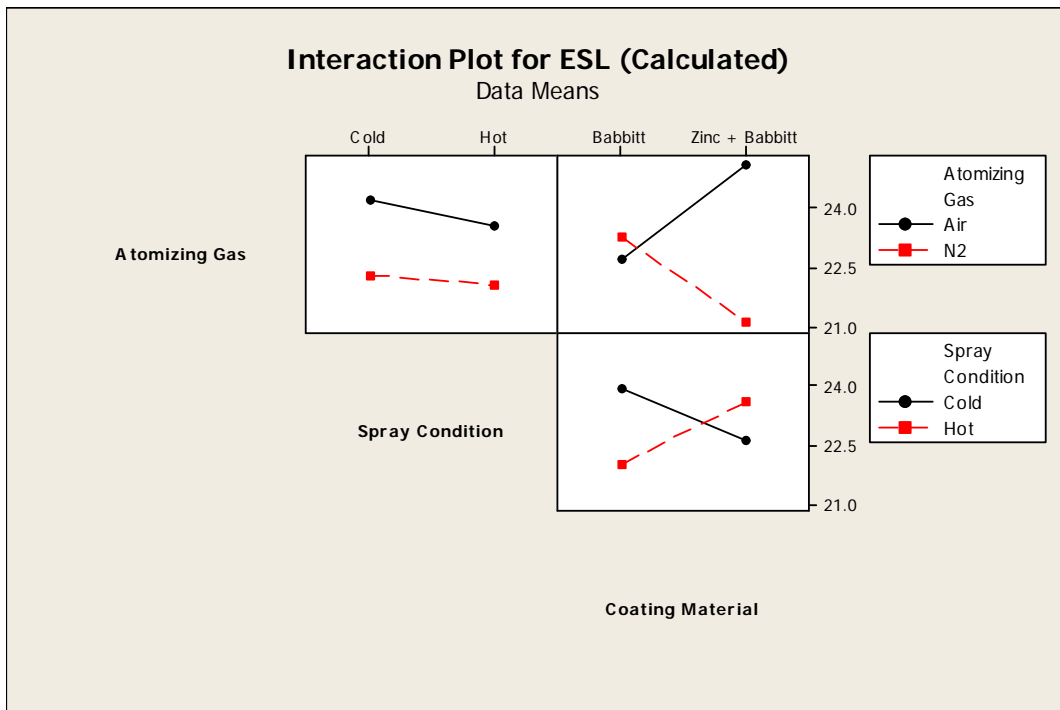


Figure 31. Interaction plots for ESL (nH).



## 4. CONCLUSIONS

The results presented in this document as well as the evidence reported by Harris *et al.*, indicate that arc sprayed Babbitt coatings provide an excellent solution for termination of an extended foil capacitor. Over 24 capacitors were sprayed at a variety of arc spray process conditions with no thermal damage to the aluminum and Mylar films in the capacitors. In addition, shorting was not observed in any capacitors, however, one capacitor did fail electrically after epoxy potting for unknown reasons. Excellent electrical performance, was observed at most spray process conditions. The results of the designed experiment do suggest that spray process conditions significantly affect capacitor electrical performance. It was concluded that Babbitt, sprayed at the Hot condition using N<sub>2</sub> as an atomizing gas provided the best electrical performance of the samples in this study. Because manufacturing costs would be reduced and fabrication would be simplified if a Zinc under layer were not used, we have selected the Babbitt, Hot, N<sub>2</sub> spray condition as our baseline process condition for capacitor termination. Coating adhesion strength was not measured or optimized, however, no delamination of the coating was observed. Based on the SAND report by Mauldin we recommend that bond strength of the Babbitt coating be investigated and that electrical discharge shock testing be conducted to be certain that the coating will not delaminate in service. We also recommend further work to minimize dust penetration and entrapment between the capacitor foils. It is likely that improved spray technique will minimize or eliminate this dust entrapment. Doing so would provide additional assurance that dust particles will not cause premature failure of a capacitor in service.





## 5. REFERENCES

1. SAND 2012-4714, Johnston, A.L., A.C. Hall, and J.F. McCloskey, *Development of the twin wire arc spray process for applying Zinc coatings to PMDI foam*, Sandia National Laboratories: Albuquerque, NM.
2. Harris, J.O., Jr., R.W. Delancy, and J.C. Foster, *Process/performance comparisons of two electroding systems for a perfluorocarbon liquid/plastic film capacitor*. 2nd European Capacitor and Resistor Technology Symposium and Seminar: CARTS-EUROPE '88, 1988.
3. Mauldin, G. H., The Development of the MC3344 Fluorinert / Mylar Energy Storage Capacitor, SAND80-2764, 1981 Sandia National Laboratories. 91 pages.
4. Harris, J.O., Jr., M.J. McDonald, and M.C. Thompson, Repetitive-pulse lifetime, statistical results of design/process factor matrix study of liquid-impregnated, discrete film/foil capacitors, in SAND90-1166C1990, Sandia National Laboratories. p. 1-7.



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